

# Calcium-rich Gap Transients: Solving the Calcium Conundrum in the Intracluster Medium

John S. Mulchaey, Mansi M. Kasliwal<sup>1</sup> and Juna A. Kollmeier

*The Observatories of the Carnegie Institution for Science, Pasadena, CA 91101*

`mulchaey@obs.carnegiescience.edu`

## ABSTRACT

X-ray measurements suggest the abundance of Calcium in the intracluster medium is higher than can be explained using favored models for core-collapse and Type Ia supernovae alone. We investigate whether the “Calcium conundrum” in the intracluster medium can be alleviated by including a contribution from the recently discovered subclass of supernovae known as Calcium-rich gap transients. Although the Calcium-rich gap transients make up only a small fraction of all supernovae events, we find that their high Calcium yields are sufficient to reproduce the X-ray measurements found for nearby rich clusters. We find the  $\chi^2$  goodness-of-fit metric improves from 84 to 2 by including this new class. Moreover, Calcium-rich supernovae preferentially occur in the outskirts of galaxies making it easier for the nucleosynthesis products of these events to be incorporated in the intracluster medium via ram-pressure stripping. The discovery of a Calcium-rich gap transients in clusters and groups far from any individual galaxy suggests supernovae associated with intracluster stars may play an important role in enriching the intracluster medium. Calcium-rich gap transients may also help explain anomalous Calcium abundances in many other astrophysical systems including individual stars in the Milky Way, the halos of nearby galaxies and the circumgalactic medium. Our work highlights the importance of considering the diversity of supernovae types and corresponding yields when modeling the abundance of the intracluster medium and other gas reservoirs.

*Subject headings:* galaxies: clusters: general – galaxies: clusters: intracluster medium – galaxies: groups: general – X-rays: galaxies: clusters – supernovae: general

## 1. Introduction

The intracluster medium (ICM) contains the majority of the baryons in clusters of galaxies. The presence of heavy elements in the ICM indicates that a substantial fraction of the diffuse gas must have passed through stars. Although the presence of iron in the ICM has been known for decades (Mitchell et al. 1976; Serlemitsos et al. 1977; Mushotzky et al. 1978), observations with *ASCA*, *Chandra*, *XMM-Newton* and *Suzaku* have provided constraints on many additional elements. In particular, the abundances of O, Ne, Mg, Si, S, Ca, Ar, Ni and Fe have now been measured in many nearby

clusters (Mushotzky et al. 1996; Fukazawa et al. 1998; Finoguenov et al. 2000; de Plaa et al. 2007; Werner et al. 2008; Bulbul et al. 2012).

Like all metals in diffuse gas, the metals in the ICM originate primarily from supernova explosions. Therefore, X-ray measurements of the composition of the ICM provide a means of studying the history of supernovae over the lifetime of the cluster. Many authors have used the abundance measurements to constrain the relative contribution of Type Ia and core-collapse supernovae to the enrichment of the intracluster medium. The abundance pattern of most clusters appears to require a  $\sim 30$ –50% contribution from Type Ia supernovae. While a combination of Type Ia and core-collapse yields can explain

---

<sup>1</sup>Hubble Fellow/Carnegie-Princeton Fellow

the observed abundances of most elements, recent work suggests such models underproduce the amount of Calcium required by X-ray observations (Werner et al. 2008; de Plaa et al. 2007). Several solutions for the Calcium problem have been suggested in the literature including the possible underestimate of Calcium yields in core-collapse models (Werner et al. 2008) or the modification of Type Ia Calcium yields based on measurements from the Tycho supernova remnant or changing the point at which deflagration transitions to detonation (de Plaa et al. 2007).

Most of the previous attempts to model the abundances of the ICM have made the simplifying assumption of uniform yields for Type Ia and core-collapse supernovae. However, extensive supernova searches over the last decade have revealed considerable diversity among supernovae and likely a wide range in yields. Here, we investigate whether including a contribution from a new class of transients that have nebular spectra dominated by Calcium can help explain the Calcium abundance in the ICM.

## 2. Calcium-rich Gap Transients

The existence of transients with spectra dominated by Calcium was first reported by Filippenko et al. (2003) based on observations from the Lick Observatory Supernova Search (LOSS; Li et al. (2011)). Perets et al. (2010) performed the first detailed study of a member of this class (SN 2005E). Subsequent examples of Calcium-rich supernovae have been found by both the Palomar Transient Factory (Kasliwal et al. 2012) and one more by the Catalina Real Time Survey (Valenti et al. 2013). Modeling the nebular spectra show that the total ejected mass of SN 2005E was very low ( $M_{ej} \sim 0.3 M_{\odot}$ ), nearly 50% of the ejected mass is in Calcium (Perets et al. 2010). The total Calcium synthesized by SN 2005E is therefore a factor of 5–10 greater than that of normal Type I supernovae.

Although only a small number of Calcium-rich supernovae have been identified so far, a strong case can be made for this representing a distinctive class of objects. All members have five distinguishing characteristics: i) peak luminosity in the gap between classic novae and supernovae; ii) rapid photometric evolution; iii) large photospheric ve-

locities; iv) early spectroscopic evolution into nebular phase and v) nebular spectra dominated by Calcium (Kasliwal et al. 2012). As the peak luminosity of these physically different explosions falls in between that of novae and classic supernovae, these objects are referred to as Calcium-rich gap transients. In addition to the characteristics given above, these events appear to occur mostly in the outskirts of their hosts or in intra-group/intracluster regions, strongly suggesting an explosion in an old population of compact binaries. Yuan et al. (2013) suggest that the locations of Calcium-rich gap transients may be consistent with globular clusters. Lyman et al. (2013) show that there is no sign of in situ star formation. No model can yet explain all the characteristics of this class.

## 3. Matching the Abundance Patterns of the Intracluster Medium

In order to understand whether the large Calcium yields of the Calcium-rich gap transients can help explain the high abundance of Calcium seen in the ICM, we examine a series of supernova models that include contributions from core-collapse, Type Ia and Calcium-rich gap transients. We compare these models to the observed ICM abundances following the procedure outlined in de Plaa et al. (2007). These ICM measurements have the advantage of being derived from a sample of 22 clusters, while most other studies have considered one cluster at a time. The de Plaa et al. (2007) dataset provides measurements for the elements of Si, S, Ar, Ca, Fe and Ni.

For each of the six elements under consideration, we perform a simple linear fit to the observed abundances:

$$\eta_{tot} \sum_i \alpha_i N_{i,j} = X_j \quad (1)$$

where  $\eta_{tot}$  is the total number of supernovae,  $\alpha_i$  are the fitted fraction for each of three supernova types,  $N_{i,j}$  is the predicted number yield of an element per supernova, and  $X_j$  is the X-ray derived intracluster abundances for each of six elements. We compute  $N_{i,j}$  from mass yields as follows:

$$N_{i,j} = \frac{Y_{i,j}}{\mu_j \xi_j} \quad (2)$$

where  $Y_{i,j}$  is the predicted mass yield for each element per supernova,  $\mu_j$  is the mean atomic mass and  $\xi_j$  is the protosolar elemental abundance taken from Lodders (2003). We adopt the yields given in Nomoto et al. (2006) for the core-collapse supernovae. Unfortunately, there has been very little theoretical work on the potential yields of Calcium-rich gap transients. Therefore, we adopt the yields given in Perets et al. (2010) for SN 2005E for this entire class of Calcium-rich supernovae.

For the Type Ia yields, we first consider the WDD2 model given in Iwamoto et al. (1999) as this has previously been shown to provide the best fits to the X-ray data (de Plaa et al. 2007). Figure 1 shows the result of taking the best-fit supernova rates given in de Plaa et al. (2007), but with 10% of the Type Ia supernovae assumed to be Calcium-rich gap transients. As can be seen from the Figure, including the Calcium-rich gap transients in the fit improves the fit ( $\chi^2$  of 21 compared to 84) for the Calcium abundance while having little effect on the other elements. Assuming the raw volumetric relative rates of supernovae improves the  $\chi^2$  to 40 (see Table 2).

If we allow the rates of each supernova type to vary, we improve the  $\chi^2$  to 2.53. Figure 2 shows this best-fit with the WDD2 model. The best-fit rate of Calcium-rich gap transients is 16% of the rate of Type Ia supernovae. We note that volumetric rate estimates for Calcium-rich gap transients relative to Type Ia supernovae vary due to the unknown luminosity function correction and small sample size. Some recent estimates are  $7 \pm 5\%$  (Perets et al. 2010),  $< 20\%$  (Li et al. 2011) and  $> 2.3\%$  from the Palomar Transient Factory (Kasliwal et al. 2012). Therefore, the best fit rate of 16% is consistent with current limits on rates from observational searches for these transients. We caution that this best-fit rate is degenerate with the Calcium yield per Ca-rich gap transient. Thus, properly accounting for this subclass of supernovae in the modeling of the ICM abundances may indeed provide a solution to the ‘‘Calcium conundrum’’ in clusters.

Next, we consider several different models for Type Ia supernovae (see Table 1) and allow the relative fraction of each supernova type to vary. In Table 2 we show the relative rates and derived  $\chi^2$  for each of the Type Ia models considered that

yielded reasonable fits. All models yield a  $\chi^2$  that is significantly better than previous work that did not take into account Calcium-rich gap transients. These models have a varying degree of success at explaining the observed abundance pattern. With the inclusion of a contribution from Calcium-rich gap transients, all of the models reasonably fit the lower atomic number elements (see Figure 3). The poor  $\chi^2$  values for most models are due entirely to the over or under production of nickel. Only the WDD2 and O-DDT models are close to reproducing the observed abundance of this element. It is worth noting that for these two models the best-fit solutions require a higher rate for Type Ia supernovae relative to core-collapse supernovae than is observed in the local volume surveys as has been found by other authors.

#### 4. Discussion

In Section 3, we showed that simply including a contribution from the recently discovered Calcium-rich gap transients can potentially explain the high Calcium abundances reported for the intracluster medium. Here we explore the implications of this conclusion and what it might mean for the enrichment process in clusters of galaxies.

Although the number of Calcium-rich gap transients studied so far is small, they appear to reside in atypical locations for supernovae (Perets et al. 2010; Kasliwal et al. 2012; Valenti et al. 2013). Examples have now been found in elliptical galaxies, above the disks of edge-on galaxies and at large distances from isolated hosts. Moreover, all of the known examples appear to be associated with groups or clusters of galaxies. The remote locations of these events suggest that these supernovae may preferentially occur in regions of low metallicity. The off-galaxy locations may also work to maximize the contribution of Calcium-rich gap transients to the enrichment of the intracluster medium in galaxy clusters. For example, the metals from Calcium-rich events in the outskirts of galaxies would be more easily stripped via ram-pressure as galaxies fall into the cluster than gas concentrated near the galaxy center. Similarly, Calcium produced in small groups of galaxies could easily be mixed in with the ICM when these systems get incorporated in to bigger

TABLE 1  
XRAY ABUNDANCES AND MODEL PREDICTIONS.

El	$\mu$	$\xi$ ( $10^5$ )	[X/Fe]	$N_{\text{Gap}}$ ( $10^{-8}$ )	$N_{\text{CC}}$ ( $10^{-8}$ )	$N_{\text{WDD2}}$ ( $10^{-8}$ )	$N_{2003\text{du}}$ ( $10^{-8}$ )	$N_{\text{W7}}$ ( $10^{-8}$ )	$N_{\text{b30}}$ ( $10^{-8}$ )	$N_{\text{ODDT}}$ ( $10^{-8}$ )
Si	28	10	$0.68 \pm 0.12$	0.0	0.4402	0.7333	0.7439	0.5562	0.1959	1.016
S	32	4.4	$0.6 \pm 0.05$	0.06974	0.3716	0.8648	0.3347	0.6068	0.1911	0.8857
Ar	36	1.0	$0.40 \pm 0.03$	0.3059	0.2175	0.6120	...	0.3598	0.1175	0.5386
Ca	40	0.63	$1.03 \pm 0.04$	5.331	0.2679	0.9596	0.05528	0.4699	0.1425	0.6713
Fe	52	8.4	$1.00 \pm 0.01$	0.8417	0.1940	1.683	1.764	1.592	1.129	1.384
Ni	56	0.48	$1.41 \pm 0.31$	0.1063	0.1544	2.081	0.8511	4.468	3.759	2.855

TABLE 2  
BEST FIT RESULTS

Rates	Model (SN Ia)	$\eta_{\text{tot}}$	$\alpha_{\text{Gap}}$	$\alpha_{\text{CC}}$	$\alpha_{\text{Ia}}$	$\chi^2$
de Plaa	WDD2	$1.34 \times 10^8$	0.00	$0.627 \pm 0.086$	$0.373 \pm 0.012$	84.3
de Plaa + Gap	WDD2	$1.40 \times 10^8$	0.037	0.630	0.333	21.1
Volumetric	WDD2	$1.62 \times 10^8$	0.030	0.701	0.271	39.9
Best Fit	WDD2	$0.99 \times 10^8$	$0.082 \pm 0.007$	$0.407 \pm 0.094$	$0.511 \pm 0.012$	2.53
Best Fit	ODDT	$0.83 \times 10^8$	$0.130 \pm 0.007$	$0.098 \pm 0.100$	$0.772 \pm 0.015$	2.21
Best Fit	W7	$1.48 \times 10^8$	$0.073 \pm 0.007$	$0.619 \pm 0.083$	$0.308 \pm 0.011$	6.84
Best Fit	B30	$2.04 \times 10^8$	$0.054 \pm 0.007$	$0.669 \pm 0.075$	$0.277 \pm 0.013$	9.63
Best Fit	2003DU	$1.70 \times 10^8$	$0.078 \pm 0.007$	$0.705 \pm 0.100$	$0.219 \pm 0.010$	9.66
Best Fit	CDEF	$2.27 \times 10^8$	$0.050 \pm 0.007$	$0.609 \pm 0.075$	$0.341 \pm 0.018$	13.03

systems.

Given the large population of intracluster stars found in clusters some Calcium-rich supernovae may also occur in-situ. Supernovae with no host galaxy have indeed been found in studies of nearby clusters (Gal-Yam et al. 2003; Dilday et al. 2010; Sharon et al. 2010; Sand et al. 2011). Such supernovae may be very efficient at polluting the intracluster medium as their metals can be directly deposited into the cluster without needing to escape the confining potential of a galaxy (Gal-Yam & Maoz 2000; Zaritsky et al. 2004; Sivanandam et al. 2009; Rasmussen et al. 2010). The recent discovery of a Calcium-rich gap transient in the Coma cluster far away from any galaxies (Kasliwal et al. 2013, in prep.) supports the idea that some Calcium-rich gap transients are indeed associated with intracluster stars. Future transient surveys should provide constraints on the importance of intracluster Calcium-rich gap transients.

Calcium-rich gap transients may also play an important role in enriching gas in other astrophysical systems. Although the uncertainties on the measurements are large, the Calcium abundance of the intragroup medium in some groups of galaxies appears to be even higher than that in rich clusters (Grange et al. 2011). This might be expected given that most of the Calcium-rich gap transients discovered to date occur in small groups and many of the stripping mechanisms at play in clusters are also effective in lower mass systems (Rasmussen et al. 2006; Kawata & Mulchaey 2008). The possible association of Calcium-rich gap transients with low metallicity regions suggests that these transients may also be an important source of enrichment in the halos of individual galaxies. This could help account for Calcium-overabundant stars in the halo of the Milky Way (McWilliam et al. 1995; Lai et al. 2009) and the large amount of Calcium in the circumgalactic medium (Zhu & Ménard 2013). Furthermore, the tendency for the Calcium abundance to track Iron rather than Oxygen in early-type galaxies (Conroy et al. 2013) suggests most of the Calcium in these galaxies is not produced by the core-collapse supernovae. Rather, the source of Calcium is likely dominated by Type Ia and Calcium-rich gap transients as we find for rich clusters (see Figure 2).

While our work suggests the potential importance of Calcium-rich gap transients on the enrichment of the intracluster medium, further study will be required to reach firm conclusions. For example, for our calculations we have relied on the yield estimates for a single supernova for the entire class of Calcium-rich gap transients. High quality nebular spectra are now available for several Calcium-rich gap transients and more detailed theoretical modeling of these spectra would provide a more representative average yield of Calcium per transient. Second, as with previous work, the core-collapse yields here include the contribution of both Type II and Type Ibc supernovae. Both the rates and the yields of each of these subtypes is different and it may be more accurate to consider their contributions separately. Third, the yields as determined by theoretical methods and nebular spectrum modeling methods are not consistent for Type Ia supernovae. More work must be done to understand these differences and their impact on the yield estimates. Finally, with the recent proliferation of all-sky transient surveys, multiple new classes of elusive explosions have been uncovered (see e.g. brief review in Kasliwal 2012 and references therein). Yield estimates for each of these new classes should be undertaken to assess their contribution to the ICM. While exploring these effects is beyond the scope of this *Letter*, we hope that our simple calculations will provide motivation for further theoretical modeling for all supernova types.

The need for more detailed supernovae modeling is further justified by upcoming X-ray missions like ASTRO-H (Takahashi et al. 2010), which will allow spatially resolved high-resolution X-ray spectroscopy for clusters for the first time. Detailed maps of the spatial variation of elements may provide important clues about the stars responsible for enriching the intracluster medium.

We are grateful to Jelle de Plaa and Esra Bulbul for providing additional insight on their previous work and thank Avishay Gal-Yam, Melissa Graham and Paolo Mazzali for helpful discussions. This work was inspired by presentations at the conference Energetic Astronomy: Richard Mushotzky at 65. We thank Chris Reynolds for his help organizing the conference.

*Facilities:* XMM-Newton, CXO

## REFERENCES

- Bulbul, E., Smith, R. K., & Loewenstein, M. 2012, *ApJ*, 753, 54
- Conroy, C., Graves, G., & van Dokkum, P. 2013, *arXiv:1303.6629*
- de Plaa, J., Werner, N., Bleeker, J. A. M., et al. 2007, *A&A*, 465, 345
- Dilday, B., Bassett, B., Becker, A., et al. 2010, *ApJ*, 715, 1021
- Filippenko, A. V., Chornock, R., Swift, B., et al. 2003, *IAU Circ.*, 8159, 2
- Finoguenov, A., David, L. P., & Ponman, T. J. 2000, *ApJ*, 544, 188
- Fukazawa, Y., Makishima, K., Tamura, T., et al. 1998, *PASJ*, 50, 187
- Gal-Yam, A., & Maoz, D. 2000, *Large Scale Structure in the X-ray Universe*, 359
- Gal-Yam, A., Maoz, D., Guhathakurta, P., & Filippenko, A. V. 2003, *AJ*, 125, 1087
- Grange, Y. G., de Plaa, J., Kaastra, J. S., et al. 2011, *A&A*, 531, A15
- Iwamoto, K., Brachwitz, F., Nomoto, K., et al. 1999, *ApJS*, 125, 439
- Kasliwal, M. M. 2012, *PASA*, 29, 482
- Kasliwal, M. M., Kulkarni, S. R., Gal-Yam, A., et al. 2012, *ApJ*, 755, 161
- Kawabata, K. S., Maeda, K., Nomoto, K., et al. 2010, *Nature*, 465, 326
- Kawata, D., & Mulchaey, J. S. 2008, *ApJ*, 672, L103
- Lai, D. K., Rockosi, C. M., Bolte, M., et al. 2009, *ApJ*, 697, L63
- Li, W., Chornock, R., Leaman, J., et al. 2011, *MNRAS*, 412, 1473
- Lodders, K. 2003, *ApJ*, 591, 1220
- Lyman, J. D., James, P. A., Perets, H. B., et al. 2013, *MNRAS*, 434, 527
- McWilliam, A., Preston, G. W., Sneden, C., & Searle, L. 1995, *AJ*, 109, 2757
- Mitchell, R. J., Culhane, J. L., Davison, P. J. N., & Ives, J. C. 1976, *MNRAS*, 175, 29P
- Mushotzky, R. F., Serlemitsos, P. J., Boldt, E. A., Holt, S. S., & Smith, B. W. 1978, *ApJ*, 225, 21
- Mushotzky, R., Loewenstein, M., Arnaud, K. A., et al. 1996, *ApJ*, 466, 686
- Nomoto, K., Tominaga, N., Umeda, H., Kobayashi, C., & Maeda, K. 2006, *Nuclear Physics A*, 777, 424
- Perets, H. B., Gal-yam, A., Crockett, R. M., et al. 2011, *ApJ*, 728, L36
- Perets, H. B., Gal-Yam, A., Mazzali, P. A., et al. 2010, *Nature*, 465, 322
- Rasmussen, J., Ponman, T. J., & Mulchaey, J. S. 2006, *MNRAS*, 370, 453
- Rasmussen, J., Mulchaey, J. S., Bai, L., et al. 2010, *ApJ*, 717, 958
- Sand, D. J., Graham, M. L., Bildfell, C., et al. 2011, *ApJ*, 729, 142
- Serlemitsos, P. J., Smith, B. W., Boldt, E. A., Holt, S. S., & Swank, J. H. 1977, *ApJ*, 211, L63
- Sharon, K., Gal-Yam, A., Maoz, D., et al. 2010, *ApJ*, 718, 876
- Sivanandam, S., Zabludoff, A. I., Zaritsky, D., Gonzalez, A. H., & Kelson, D. D. 2009, *ApJ*, 691, 1787
- Takahashi, T., Mitsuda, K., Kelley, R., et al. 2010, *Proc. SPIE*, 7732, 27
- Tanaka, M., Mazzali, P. A., Stanishev, V., et al. 2011, *MNRAS*, 410, 1725
- Valenti, S., Yuan, F., Taubenberger, S., et al. 2013, *arXiv:1302.2983*
- Werner, N., Durret, F., Ohashi, T., Schindler, S., & Wiersma, R. P. C. 2008, *Space Sci. Rev.*, 134, 337
- Yuan, F., Kobayashi, C., Schmidt, B. P., et al. 2013, *MNRAS*, 432, 1680

Zaritsky, D., Gonzalez, A. H., & Zabludoff, A. I.  
2004, *ApJ*, 613, L93

Zhu, G., & Ménard, B. 2013, *ApJ*, 773, 16

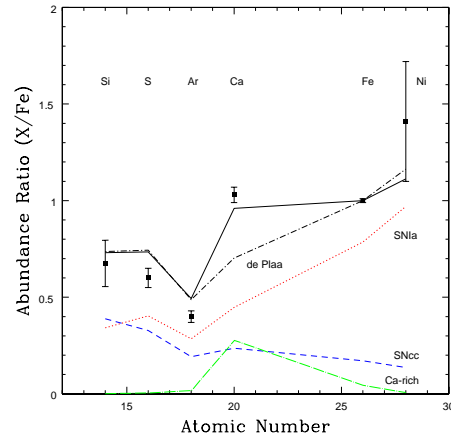


Fig. 1.— Abundance ratios relative to iron versus atomic numbers for the cluster sample given in de Plaa et al. (2007). We show the contributions of the three types of supernovae (Type Ia, core-collapse and Calcium-rich gap transients) assuming the best-fit supernovae rates given in de Plaa et al. (2007), but with 10% of the Type Ia’s assumed to be Calcium-rich gap transients. The solid black line shows the total abundance ratio. The best-fit found by de Plaa et al. (2007) considering only the contribution from Type Ia’s and core-collapse supernovae is shown by the black dot-short dash line. The inclusion of a contribution from the Calcium-rich gap transients increases the overall Calcium abundance, but has little impact on the other elements.

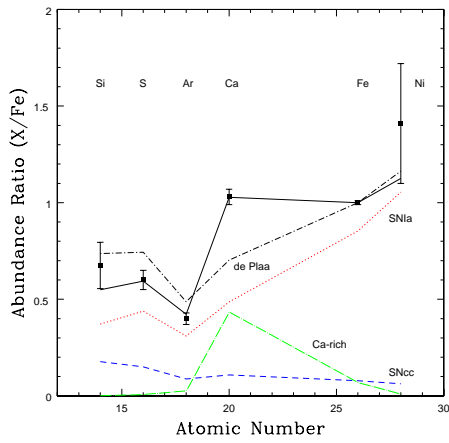


Fig. 2.— Same as Figure 1, but with the rates of each supernovae type allowed to vary.



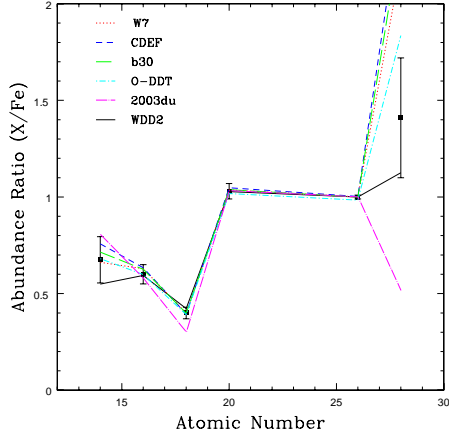


Fig. 3.— Fits to the data given in Figure 1 using the yields from a number of different Type Ia models. The core-collapse and Calcium-rich gap transients yields are the same as those used in Figure 1, but the rates for each supernovae type were allowed to vary. While all of the Type Ia models can reproduce the lower atomic number elements, most over or under produce Nickel.